DESIGN & CONSTRUCTION
OF A
BOUCHEROT INDUCTION MOTOR

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A BOUCHEROT INDUCTION MOTOR.

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The object of this work is to design a Boucherot rotor to be used in a 10 HP, G.E. 25 Cycle, 80 Volt, 4 Pole, 2-3 Phase Induction Motor.

The only difference between a Boucherot Induction Motor and the ordinary squirrel cage type is in the rotor. Instead of having one squirrel cage, the Boucherot Motor has two or more placed one inside the other. The object of the two squirrel cages is to give the rotor a better starting torque with less current consumption and also to give a better running characteristic.

FIGURE I. shows the method of placing the two sets of windings. The outer winding has a high resistance and relatively low inductance. The inner winding has a low resistance and high inductance due to the greater leakage surface. At the start the frequency of the flux in the rotor equals the stator frequency, hence the high inductance cage will carry practically no current. The outer winding or low inductance winding will furnish the torque, and since the resistance of this winding is high and practically equal to the reactance, we will get maximum torque at the start. Under running conditions the frequency of the flux in the rotor will be proportional to the slip and since the slip is small the frequency will be small and the reactance of the inner winding will be small. The impedance of the inner winding will therefore be small under

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Fig 1

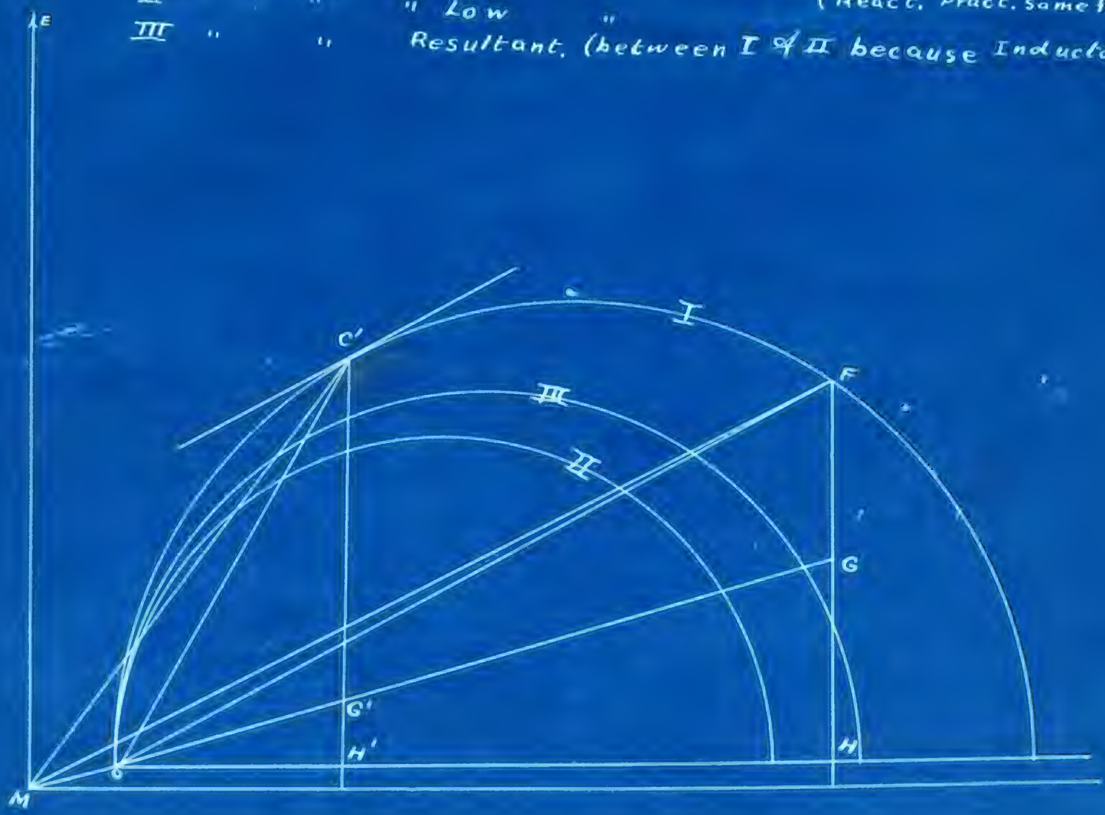
Stampings for 10 HP Induction Motor

Double Rotor Conductors.

Thickness of Stampings No

Scale 6" = 1'

I Circle Diagram for present Winding & also for high Res Winging
II " " " Low " (React. Pract. same for both)
III " " Resultant. (between I & II because Inductances in II)



running conditions and it will furnish the torque or the greater portion of the torque at a minimum slip.

the total characteristic is shown by curve 3, FIG. 2, which is the resultant of curves 1 and 2. Where 1 is the curve for the high resistance winding and 2 is the curve for the low resistance winding.

An idea of the running and starting characteristics of the Boucherot Rotor can also be obtained from the circle diagram of each winding. The inner winding will have a smaller circle than the outer winding, because the reactance of the inner winding is greater. The resultant quantities can be obtained by the vecter addition of these two circles, i.e., we would have to know the phase and magnitude of the curre~~o~~nts in each one at the same time and by adding them vectorially we would obtain the resultant circle diagram. The diameter of the resultant circle would be equal to

$$\frac{E}{X_1 - X_2}$$

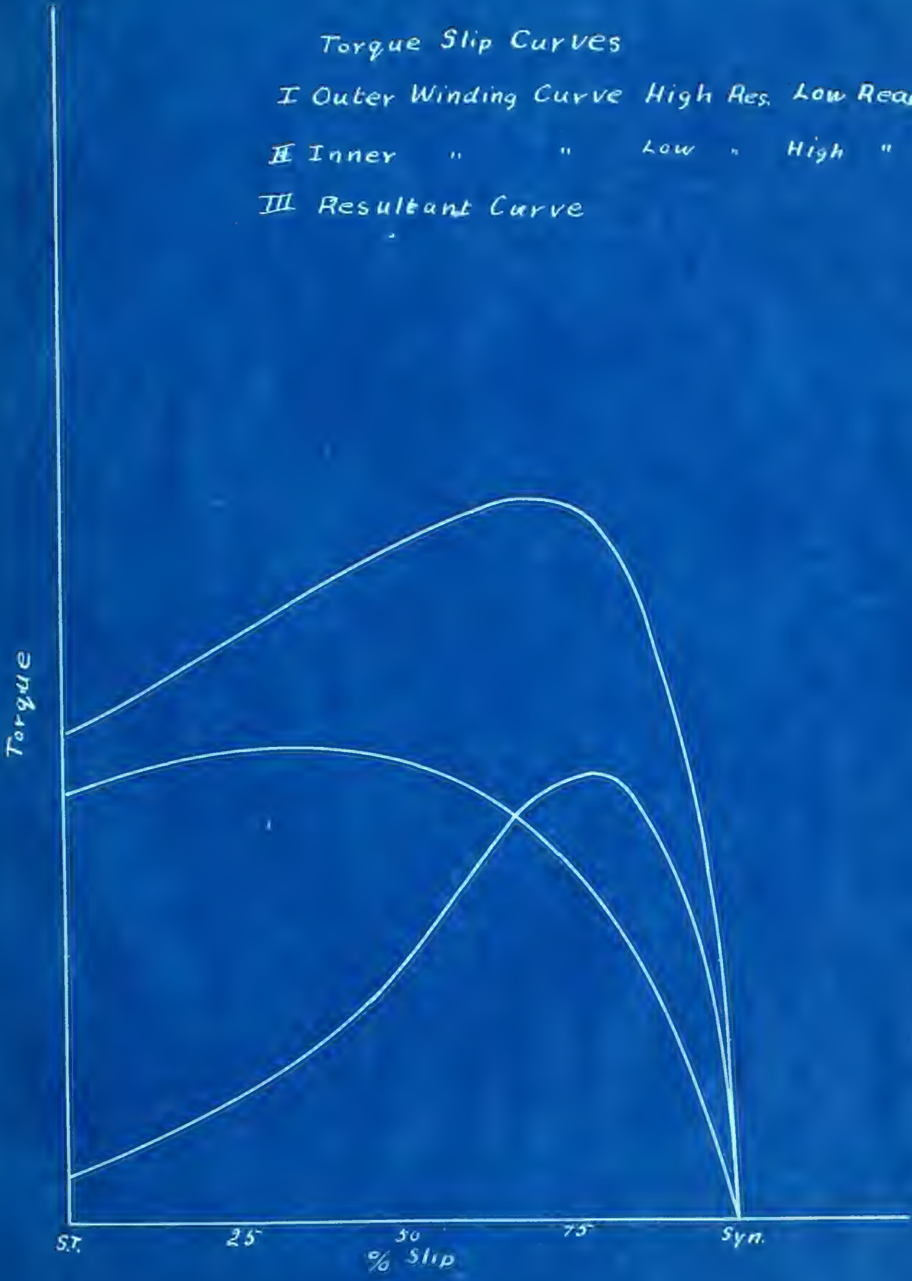
Where E - impressed E M F of primary

X_1 - primary reactance

X_2 - secondary " reduced to primary reactance.

X_2 is the resulatant reactance of the two winding. The windings may be considered as in parallel because the current in any winding is proportional to the impedance of that winding. The easiest way to find the impedance of the two windings would be to find the admittance and take the reciprocal as the impedance.

Fig 2


Torque Slip Curves
I Outer Winding Curve High Res. Low Reac.
II Inner " " Low " High "
III Resultant Curve
Torque
S.T.
25
50
75
Syn.
% Slip

In designing the rotor our object was to obtain a maximum torque at starting and minimum slip at normal full load. This being our object we found it would be easier to obtain the component circles first and then determine the resultant circle diagram.

Calculations

Motor runnigg No Load. 25 Cycles. 3 ϕ.

$E = 80$ Volts

$I_{pe} = 32.8$ Amps. Exciting current.

$W_1 = -1000$ $W_2 = 1700$ Exciting Loss = 700 W.

Rotor Blocked. 25 ~

$E = 14.5$ Volts $R_p = .0647^{\Omega}$ D.C.

$I_p = 95$ Amps

$W_1 = 1350.$ $W_2 = 450$ $W = 1800$

Cal. for Circle Diagram (Eqivalent Single ϕ.)

$I_{peq} = \sqrt{3}\, I_{pe} = \sqrt{3} \times 32.8 = 57$ A.

$\cos\phi = \dfrac{700}{\sqrt{3}\ 80 \times 32.8.} = .1536.\ \phi = 8°50'$

Rotor Blocked 80 V. Eq. Single ϕ I.

Assume $I \propto E$

$\dfrac{I}{80} = \dfrac{95}{14.5}$ $I = 524$

$I_{eq} = \sqrt{3} \times 524. = 910$ Amp.

$\cos\phi = \dfrac{1800}{\sqrt{3} \times 14.5 \times 95} = .754.\ \phi = 41°$

Primary Copper Loss at 80 V.

$= \frac{3}{2} I^2 R = \frac{3}{2} \times 524^2 \times .0647. = 26700$ W.

$\dfrac{26700}{80} = 334.$ Amp.

I_{eq} at 10 HP. $= \dfrac{7460}{80} = 93.4$ Amp.

High Res. Winding.

From Diagram.

C' is point PT of tangency of a line // to OG.

$$\frac{R_{sk}}{R_p} = \frac{G'C'}{G'H'} = \frac{11.52 \times .03235}{5.98} = R_{sk}.$$

$R_{sk} = .0622$ R_p = Eq. Single ϕ Res $= \frac{1}{2} \times .0647$

Rsh is the Res. that x by the sec. current gives the sec. copper loss

Rsh the effect. res. is $\propto$ to the calculated res.

Rsh = k Rcalculated from size + length of conductors.

Res. of winding of present rotor is also $\propto$ to its calculated Res. i.e. $R_{pres} = k\, R'_{calculated}$

R_{pres} from diagram = .0338 Effective.

R' = Res. of conds. + Res. of Ring.

Res. of each conductor. $= \frac{K'L}{A}$

$$= .0000084833 \frac{\frac{7}{12}}{.35 \times .5}$$

$$= .0000283^{\omega}$$

Since there are 4 poles there will be 4 paths in //. Current in rotor varies from a max. under the pole to zero midway between poles. (a dist. of 90 electrical degrees This is eqivalent to a res R. varying from ~~ZE~~ R to infinity. $\therefore R_x = R \times \frac{1}{\cos x}$

$R = .0000283^{\omega}$

$$R_x = .0000283 \cdot \frac{1}{\cos x}$$

Since there are 47 Cond. the dist. between each conductor $= \frac{720}{47} = 15.3°$

For 15.3° there are 6 conductors approx.

Res. of conductors [redacted] = R_c

$$\frac{1}{R_c} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} + \frac{1}{R_5} + \frac{1}{R_6}$$

$R_1 = .0000283.^{\omega}$

$R_2 = \frac{1}{\cos 15.3} \times .0000283 = .0000294.$

$R_3 = \frac{1}{\cos 30.6} \times .0000283 = .0000328.$

$R_4 = \frac{1}{\cos 45.9} \times .0000283 = .0000407$

$R_5 = \frac{1}{\cos 61.2} \times .0000283 = .0000588$

$R_6 = \frac{1}{\cos 76.5} \times .0000283 = .0001215$

$R_c = .00000674$

Since there two cond. per. ϕ.

Total $R_c = 2 \times .00000674 = .00001348^{\omega}$

Res. of present rings. = R_r

$R_r = R_1 + R_2 + R_3 + R_4 + R_5 + R_6$

$R_1 +$ - - - — - - - - - R_6 = res. of elementary element between cond.

$R_1 = \frac{kL}{A} = .0000008483 \times \frac{\frac{.867}{12}}{.795} = .000000765.^{\omega}$

$R_2 = \frac{1}{\cos 22.95} \times .000000765 = .00000083.$

$R_3 = \frac{1}{\cos 38.25} \times .000000765 = .000000974$

$R_4 = \frac{1}{\cos 53.55} \times .000000765 = .000001285.$

$R_5 = \frac{1}{\cos 68.85} \times .000000765 = .00000211.$

$R_6 = \frac{1}{\cos 84.15} \times .000000765 = .0000075.$

$R_r = .000011354$

Total $R_r = 2 \times .000011354 = .000022708.^{\omega}$

$R' = 000022708 + 00001348 = 000036188^{\omega}$

This is the calculated Res. of 1/4 of the rotor, or between poles.

$R_{pres} = k R'$

$.0338 = k .000036188.$

$k = 935.$

Cal. res. of high res. winding $= R'_{sh}$

R_{sh}. eff. $= .0622$

$R'_{sh} = \dfrac{.0622}{935} = .0000665^{\omega}$

= res. of conds. + res of ring.

Assume diam. of cond. = .4"

by similar calculations as above the res. of con

= .0000224

res. of rings = $0000665 - 000224 = .0000441^{\omega}$

$0000441 = \dfrac{kl}{A} \qquad kl = 000018804$

For copper A = .449 sq.in.

for iron $5.44 \times .449 = 2.45$ sq in

for one ring $A = \dfrac{2.45}{2} = 1.225$ sq.in.

Low res. Winding.

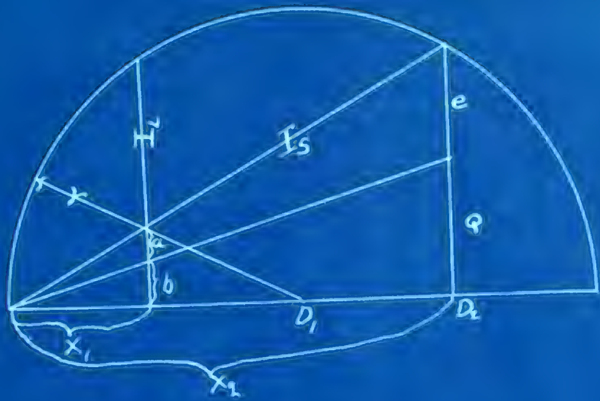
Assume 2% slip. Eff. res. from geometr of circle diagram = .01495

Cal. $R = \dfrac{.01495}{935} = .000016$

Assume diam of cond = 1/2"

By similar calculations as before.

A = 2.575 sq.in. copper.



Reactance Calculations.

Calculations for inner winding diamete of circle diagram.

$$\text{Assume slip} = 2\% = \frac{a}{I_L + a} = \frac{a}{93.4 + a}$$

$$a = 1.905 \text{ amp.}$$

$R_p = .0325^{\omega}$ $\qquad R_s = .01495$ assumed.

$$R_s^{H} = .0622$$

$$\frac{a}{b} = \frac{e}{Q} = \frac{R_s}{R_p} = \frac{.01495}{.03235} = .464$$

$$I_s^2 R_s = e80$$

$$I_s^2 = \frac{80}{.01495} e = 5355 e$$

$$I_s^2 = (e + Q)^2 + X_2^2$$

$$5355 e = (e + Q)^2 + X_2^2$$

$$e = .464 \; Q$$

$$\therefore \text{subst.} \quad 2480 Q = (.464 Q + Q)^2 + X_2^2$$

$$X_2^2 = 2480 Q - 2.146 Q^2$$

$$(X_1 - r)^2 + (I_2 + a + b) = r^2$$

$\frac{a}{b} = .464$

$\therefore\ b = \frac{1.905}{.464} = 4.1$

$(X_1 - r)^2 + (93.4 + 1.905 + 4.1)^2 = r^2$

(1) $X_1^2 - 2X_1 r + 9900 = 0$

$(X_2 - r)^2 + (e + Q)^2 = r^2$

$X_2^2 - 2rX_2 + (.464\ Q + Q)^2 = 0$

(2) $X_2^2 - 2rX_2 + 2.146\ Q^2 = 0$

Value of r from (1)

$r = \frac{9900 + X_1^2}{2\ X_1}$

Now $\frac{a+b}{e+Q} = \frac{X_1}{X_2}$ or $X_1 = \frac{1.905 + 4.1\ X_2}{1.464\ Q}$

$= 4.1\ \frac{X_2}{Q}$ $\qquad \frac{X_2}{X_1} = \frac{Q}{4.1}$

sub in (2)

$2480\ Q - 2.146\ Q^2 - \frac{2X_2\ (9900 + X_1)^2}{2\ X_1} + 2.146\ Q^2 = 0$

$2480\ Q - \frac{Q}{4.1}\left\{9900 + \frac{4.1^2}{Q^2}\left(2480Q - 2.146\ Q^2\right)\right\} = 0$

$2480\ Q - 2410\ Q - 10200 + 8.8\ Q = 0$

$78.8Q = 10200$

$Q = 129.5$

Solve 2 for

$2480 \times 129.5 - 2 \times 535\ r = 0$

$r = \frac{322000}{1070} = 301$ amp.

diameter of circle $= 2 \times 301 = 602$

total reactance of primary & low res.

secondary. $= \frac{80}{602} = .1335^{\omega}$.

Reactance of present winding & also of

high winding. $= \frac{80}{1370} = .0584^{\omega}$

reactance of low winding

$= .1335 - .0584 = .0751$ = reactance of holes & slots.

reactance of the holes $= 2Cf L_s n_1^2 \frac{N_1 P_1'}{N_2 P_2'} (.625) 10^{-7}$

$= 2 \times .75 \times 25 \times 5 \times 6^2 \frac{24^2 \times 3}{4 \times 11.75} (.625) 10^{-7} = .0155$

= react per ϕ

Now .0751 is the eq. single ϕ reactance & must be reduced to 3 ϕ quantity by mult. by $\frac{3}{2}$

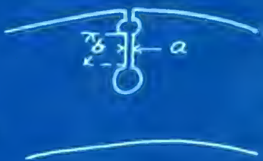
X per $\phi = \frac{3}{2} \times .0751 = .1130$

Reactance of the slot

$= .1130 - .0155 = .098$

$.098 = 24800 \times \frac{b}{a} \times 10^{-7}$

$\frac{b}{a} = 3.95$



Calculations of reactances of seperate parts $\frac{b}{a} = 3.35$

assume $a = \frac{3}{16}''$

$b = .627''$

Since reactance per $\phi = X = .098$

$= 2 C f L n_1^2 \frac{N_1^2 p_1'}{N_2 p_2'} \times \frac{b}{a} 10^{-7}$

$= 2 \times .75 \times 25 \times 5 \times 6^2 \times \frac{24^2 \times 3}{4 \times 11.75} \times \frac{b}{a} 10^{-7} = 24800 \frac{b}{a} \times 10^{-7}$

C O N S T R U C T I O N

Owing to the peculiar form of the stamping that would be required to make up the laminated core of this rotor, it was found necessary to form them by another method than stamping. For this reason and the difficulty entailed in cutting and fitting the laminations, it was decided to do without a spider and fit the laminations directly on the shaft.

The laminations where cut from sheet iron and placed on a specially made arbor with a shoulder on one end and a thread on the other. In order to drill the hole in the laminations to fit on the arbor,a special drill the required size had to be made. Two cast iron flanges, FIG. 4, were made to fit the arbor and the laminations screwed up between them, placed in a lathe and turned down to size.

Before putting the laminations on the arbor one flange was laid off and holes drilled 1/16" larger than the conductors as in Fig. 1. This was used as guide in drilling the holes in the laminations. For this drilling extra long drills had to be obtained. After drilling the work was placed in a milling machine and slots cut. It was then taken apart, the laminations cleaned up and placed on the shaft made similar to the one in Fig. 3, with the exception that a thread was cut on one end. One flange was fastened in position with set screws and the laminations tightened up on the shaft.

The flanges were cut off to allow the end rings Fig. 5, to be placed in position. The copper bars were cut to allow a projection of 1-1/4" on either side. The 1/2" bars were cut down to 3/8" diameter for this distance of 1-1/4".

[illegible]

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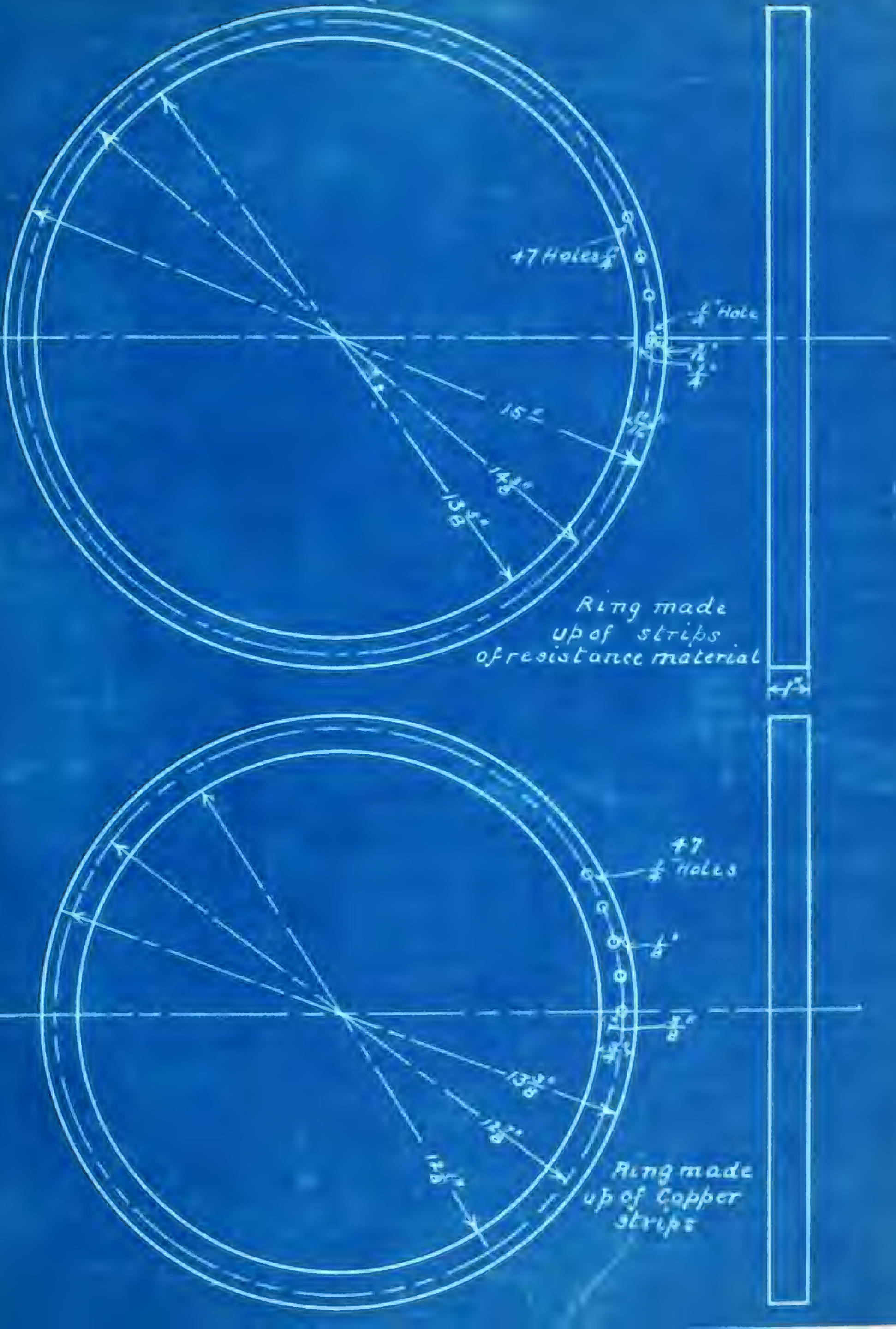
Fig. 3.

Induction Motor Shaft
Scale 4" = 1'

Fig 4

Fig 5



47 Holes
Hole
15
14 3/8"
13 5/8"
Ring made
up of strips
of resistance material
47
Holes
13 3/8"
12 5/8"
Ring made
up of Copper
Strips

Ordinary paper was used for insulation. The end rings, the inner one of brass to provide a low resistance, and the outer of cast iron for the high resistance, were fastened on with brass nuts. The completed rotor was then filed to exact size and placed in the stator where it ran satisfactorily.

Due to the fixed dimensions of the rotor it was necessary to change the calculated values to the values shown on the blue prints.

After the completion of the new rotor we ran a test on it to obtain the exciting and rotor blocked current, (which is a measure of the instantaneous starting current.

Data obtained for new rotor.

Motor running no load. - Exciting current.

$E = 80$, $I = 23\text{-}5/10$, average

$W_1 = 1300$ $W_2 = 340$, $W = 960$ watts.

Rotor blocked

$E = 25$, $I = 72.5$ average

$W_1 = 1650$, $W_2 = 200$, $W = 1850$ watts.

As seen from the data the exciting current is much smaller for the new rotor than the old; this is probably due to the smaller iron loss and slightly less air gap. The power consumed is greater, but this might be due to the newness of the moving parts.

The rotor blocked quantities are about 50% smaller for the new rotor than for the old.